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Effects of Anomalous Z^0 Decays on Neutrino Counting Near the Z^0 Peak

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Abstract. We study the implications of the anomalous Z^0 decays on neutrino counting in e^+e^- collisions. The $Z^0 \to l\bar{l}\gamma$ vertex is parametrized by an effective Lagrangian, L_{eff}, satisfying $U(1)_{\mathrm{em}}$ gauge invariance, CP and chirality conservation. The parameters of L_{eff} are constrained by the ratio $\Gamma(Z \to l\bar{l}\gamma)/\Gamma(Z \to l\bar{l})$, Bhabba scattering, and low energy $\nu_\mu e$ scattering data. We find that the effect on neutrino counting can be significant but depends on the magnitude and relative signs of the parameters in L_{eff}. We also find that accurate measurements of the cross-section $\sigma(e^+e^- \to \nu\bar{\nu}\gamma)$ at the Z^0 peak can be used as a sensitive test for new physics.

Hard photons associated with leptonic Z^0 decays have been observed by both the UA1 and UA2 experiments [1, 2] at the CERN SPS $p\bar{p}$ collider at a rate greater than expected from radiative corrections. Although the results are preliminary and more data will certainly be required before their significance can be determined, these events are widely viewed as indicating the existence of new physics [3] beyond the standard electroweak theory. In this paper we look at implications that these events are due to new physics occurring at or above 100 GeV and not just a statistical fluctuation of ordinary QED bremstrahlung processes. We parametrize the new physics by a local effective Lagrangian [4], L_{eff}, involving the photon field, the neutral gauge boson field, and the leptonic current of electrons and neutrinos. We constrain the parameters of L_{eff} using $\Gamma(Z \to l\bar{l}\gamma)/\Gamma(Z \to l\bar{l})$, Bhabba scattering, and low energy $\nu_\mu e$ scattering data. The effective Lagrangian is then employed to study effects of the anomalous events on the counting of neutrino species, N_ν, at e^+e^- colliders.

In constructing the effective Lagrangian we assume that Λ, the scale at which any Z^0 substructure would be revealed, is greater than M_z. This is a consistency requirement to make sense of an effective $\gamma Z^0 l\bar{l}$ vertex. We assume CP invariance and following Drell and Parke [4] we also assume chiral invariance. Unlike [4] the third assumption we make is to give up $SU(2)\times U(1)$ invariance at the scale Λ. This is one possible interpretation of the non-observation of $W^\pm \to l^\pm \nu\gamma$ events, and thus our results complement those of [4]. Many composite models [5] of the Z^0 have this feature; however, it is also necessary for these models to perform unattractive adjustment of parameters so as not to disturb the observed $SU(2)\times U(1)$ symmetry in low energy experiments. The only gauge invariance L_{eff} respects is $U_{\mathrm{em}}(1)$. The lowest dimension operator available that is consistent with the above assumptions is of dimension six. In momentum space it is given by

$$L_{\mathrm{eff}} = \frac{1}{\Lambda^2}\sum_{l=e,\mu,\tau}[c_L^l \bar{l}\gamma_{\sigma L} l + c_R^l \bar{l}\gamma_{\sigma R} l + \tfrac{1}{2}c^\nu \bar{\nu}\gamma_{\sigma L}\nu]\,\varepsilon^{\mu\nu\sigma\rho}k_\mu e_\nu^\gamma e_\rho^z \tag{1}$$

where k^μ is the four momentum of the photon and $e^\gamma(e^z)$ is the polarization vector of the photon (Z-boson). CP invariance requires that c_L^l, c_R^l and c^ν be relatively real and we choose them to all be real. For simplicity we assume universality in the C^l's for the charged leptons. A similar effective Lagrangian can be written for quarks, however, in this paper we only concern ourselves with leptons.

Next we determine the constraints on the parameters in L_{eff}. The rate of $Z^0 \to e\bar{e}\gamma$ versus $Z^0 \to e\bar{e}$ determines a combination given by

$$r = \frac{\Gamma(Z^0 \to l\bar{l}\gamma)}{\Gamma(Z^0 \to l\bar{l})} = \frac{(c_L^{l2} + c_R^{l2})}{80\pi^2 G^2(1 - 4x_w + 8x_w^2)}\left(\frac{M_z}{\Lambda}\right)^4 \tag{2}$$

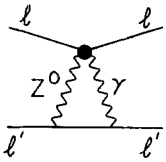

Fig. 1. Feynman diagram for lepton–lepton scattering with anomalous Z^0-photon–lepton interaction denoted by the blob

where $x_w \equiv \sin^2\theta_w$, $G \equiv g/\cos\theta_w$ with g being the $SU(2)$ coupling constant in the standard model, and M_z is the Z-boson mass. For our numerical estimate, we take $r = 0.1$ for each leptonic mode [7]. This gives the equation

$$(c_L^{l2} + c_R^{l2})\left(\frac{M_z}{\Lambda}\right)^4 \simeq 23.7. \tag{3}$$

Further constraints on the parameters can be derived by computing the effects of the phenomenological interaction (1) in low energy experiments. The relevant ones, as well as being the most stringent, are Bhabba scattering and $\nu_\mu e$ elastic scattering. To this end we calculate the effective one-loop local four-fermion interaction given by the Feynman diagram of Fig. 1.

The integrals involved are divergent and we take the cut-off to be Λ, since, beyond this the effective Lagrangian is not valid. The resulting 4-fermi interaction for $\nu_\mu e$ scattering is

$$I_{\nu e} = \frac{3}{32\pi^2}\frac{c^\nu}{\Lambda^2}\ln\left(\frac{\Lambda^2}{M_z^2}+1\right)\bar{\nu}_\mu\gamma_L^\sigma\nu_\mu \cdot[g_L\bar{e}\gamma_{\sigma L}e - g_R\bar{e}\gamma_{\sigma R}e], \tag{4}$$

where $g_L = G(1-2x_w)/2$ and $g_R = -Gx_w$. We compare this with the standard model result and use the experimental data on neutral currents [8], which is in agreement with the standard model, to arrive at the following constraint:

$$c^\nu\left(\frac{M_z}{\Lambda}\right)^2 \ln\left(\frac{\Lambda^2}{M_z^2}+1\right) \lesssim 5.5. \tag{5}$$

Repeating this procedure, we obtain the effective four fermion interaction for Bhabha scattering to be:

$$I_{ee} = \frac{3}{8\pi^2\Lambda^2}\ln\left(\frac{\Lambda^2}{M_z^2}+1\right)[c_L^e g_L \bar{e}\gamma_L^\mu e\ \bar{e}\gamma_{\mu L}e - c_R^e g_R \bar{e}\gamma_R^\mu e\ \bar{e}\gamma_{\mu R}e + (c_R^e g_L - c_L^e g_R)\bar{e}\gamma_L^\mu e\ \bar{e}\gamma_{\mu R}e]. \tag{6}$$

Since the data [9] agrees very well with QED we obtain the following stringent bound

$$|c_L^e + c_R^e|\left(\frac{M_z}{\Lambda}\right)^2 \ln\left(\frac{\Lambda^2}{M_z^2}+1\right) \lesssim 1.07 \tag{7}$$

Equations (3), (5) and (7) tightly constrain L_{eff}. In fact, if c_L^e and c_R^e have the same sign, using the Schwartz inequality and (3) and (7) we obtain

$$\Lambda \lesssim 120\,\text{GeV} \tag{8}$$

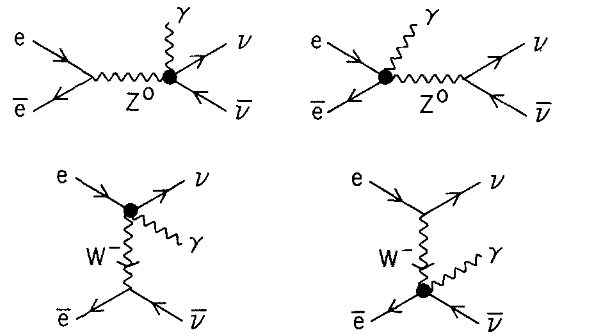

Fig. 2. Feynman diagram depicting contribution of anomalous gauge boson–photon–lepton interaction to the process $e + \bar{e} \to \nu\bar{\nu}\gamma$

which is barely consistent with our approximation of locality. On the other hand if c_L^e and c_R^e have opposite signs, Λ is allowed to increase. Indeed, if $c_R^e = -c_L^e$ then (7) is trivially satisfied for all values of Λ.

With these constraints on the parameters of L_{eff} we calculate its effects on neutrino counting near the Z^0-peak. In addition to the Feynman diagrams of the standard model [10], L_{eff} generates amplitudes given by the graphs of Fig. 2. The W-boson exchange diagrams in Fig. 2 are small as noted before and we neglect them. The interference between the amplitudes given by Fig. 2 and those of the standard model give either zero or very small contributions when the two-neutrino phase-space is integrated over. In the limit that the t-channel W-exchange process for the standard amplitudes is approximated by $M_w \to \infty$, the interference between the new amplitudes of Fig. 2 and the standard model amplitudes give no contribution to the cross section. This approximation is good at center of mass energies, E^*, not much above M_z and improves at lower energies. Our numerical calculation confirms this. After evaluating these amplitudes, the contribution to the differential cross-section with respect to the photon energy for the process $e\bar{e} \to \gamma\nu\bar{\nu}$ due to L_{eff} is given by

$$\frac{d\sigma}{dx} = \frac{G^2 N_\nu}{9216\pi^3}\frac{S}{\Lambda^4}x^3\left(1-\frac{x}{2}\right) \cdot\left\{\frac{(g_L^2+g_R^2)c_\nu}{(1-\rho)^2+\sigma^2} + \frac{(c_L^e)^2+(c_R^e)^2}{(1-x-\rho)^2+\sigma^2} + \frac{2c_\nu(g_R c_R^e + g_L c_L^e)[(1-x-\rho)(1-\rho)+\sigma^2]}{[(1-\rho)^2+\sigma^2][(1-x-\rho)^2+\sigma^2]}\right\} \tag{9a}$$

where

$$\rho \equiv \frac{M_z^2}{S} \tag{9b}$$

$$\sigma \equiv \frac{\Gamma M_z}{S} \tag{9c}$$

$$x \equiv 2\frac{E_\gamma}{E^*} = \frac{2E_\gamma}{\sqrt{S}} \tag{9d}$$

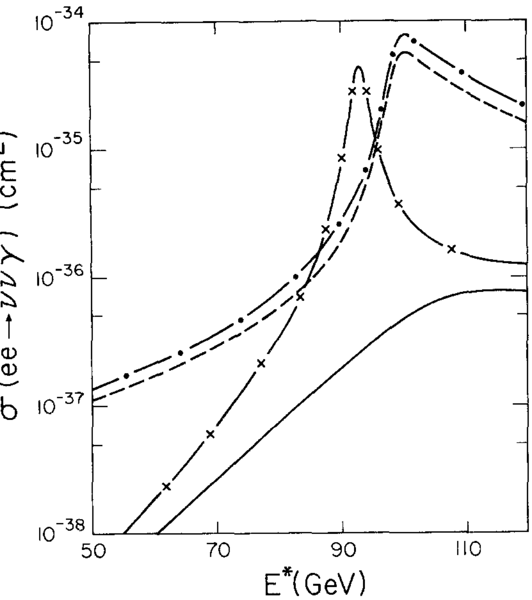

Fig. 3. The cross-section of $e + \bar{e} \to \nu\bar{\nu}\gamma$ due to the standard model and the anomalous interaction L_{eff}. The dash line denotes the standard model cross-section for $N_\nu = 3$ and the dash-dot line for $N_\nu = 4$. The solid line is for contribution of L_{eff} with $c^\nu = 0$ and the dash-cross line is for $c^\nu = 7.9$, $c_L^e = c_R^e = 13.86$ and $\Lambda = 120\,\mathrm{GeV}$

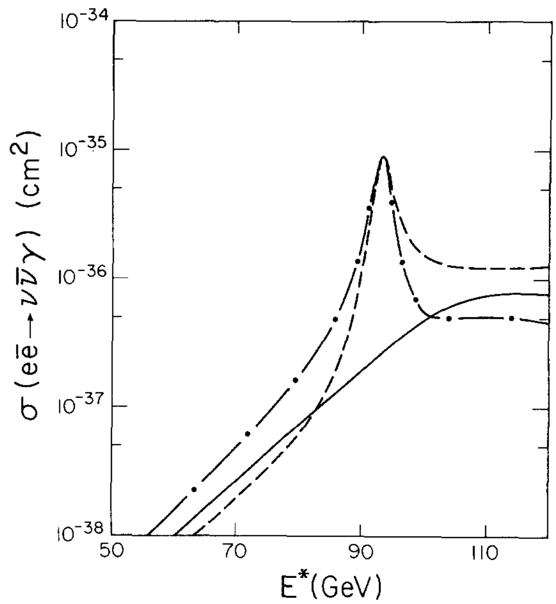

Fig. 4. Comparison of the effect of L_{eff} on $\sigma(e\bar{e} \to \nu\bar{\nu}\gamma)$ for different parameters. The solid line is for $c^\nu = 0$. The dot-dash line is for $c^\nu = 7.9$, $c_L^e = -c_R^e = 13.86$ and dash line is for $c^\nu = -7.9$, with the same values for c_L^e and c_R^e

and Γ is the width of the Z^0 which is taken to be $2.5\,\mathrm{GeV/c^2}$. The number of neutrino species is given by N_ν. The anomalous contribution to the cross-section is obtained by integrating over the photon spectrum of (9a) from a minimum value x determined by the acceptance of photon energy in a given experiment to $x = 1$.

For comparison with the standard model contribution, which has an infra-red divergence [10], we integrate $x = 0.1$ to $x = 1$. Since we are interested in the effects of the anomalous term we take $N_\nu = 3$ for (9a) and compare it with $N_\nu = 3$ and 4 for the standard model cross-sections [11] which are given by the dashed line and the dash-dot line of Fig. 3 respectively. Figure 3 also reveals that if $c_\nu = 0$ the effect of L_{eff} is about 1% at $E^* = 100\,\mathrm{GeV}$. However, if $c_\nu \neq 0$ but takes the maximum value allowed by the constraint of [5] i.e. $c_\nu = 7.9$, and taking $\Lambda / M_z = 1.32$, a large effect is seen [see the dash-cross curve]. These parameters give a width of $\Gamma(Z^0 \to \nu\bar{\nu}\gamma) = 1.9\,\mathrm{MeV}$ which is very small. It is quite clear that a peak will appear at $E^* = M_z$ if $c_\nu \neq 0$. Such a large value for c_ν would probably indicate a "strong" interaction for the underlying structure. In Fig. 4 we display the results of a non-vanishing c_ν and how they change when the relative phase of c_ν and c_e are altered. The parameters we use are $c_\nu = 7.9$, $c_{eR} = -c_{eL} = 13.68$ and $M_z/\Lambda = 1/2$. The larger effect occurs when c_ν and c_e are relatively negative being two to three times as large as when they are of the same sign. As expected the difference is small near the Z^0-peak. The results presented in Fig. 3 and 4 are to be added to the standard model ones to give the total cross-section. Both the standard model and L_{eff} give contributions to the cross-section that are approximately proportional to N_ν since in both cases the W-exchange channel is small.

In conclusion we find that the anomalous L_{eff} is barely consistent with low energy data if c_L^e and c_R^e are of the same sign while there is no problem if c_L^e and c_R^e have opposite signs. The effect on neutrino counting is dramatic if $c_\nu \neq 0$. Indeed one can take the opposite point of view and use the measurement of the cross-section $\sigma(e\bar{e} \to \nu\bar{\nu}\gamma)$ at the Z^0-peak as an indication of new physics. Comparing the results of Figs. 3 and 4 we see that measuring the cross-section $e\bar{e} \to \nu\bar{\nu}\gamma$ both below and above the Z^0-peak is very important in constraining the parameters of L_{eff} in the event that no effects are found. If one's interest is in determining N_ν and wants to avoid the possible adulteration from L_{eff} the value of $E^* \simeq 100\,\mathrm{GeV}$ appears to be most suitable.

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relative phases of the parameters in L_{eff} and L_{std} are real
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